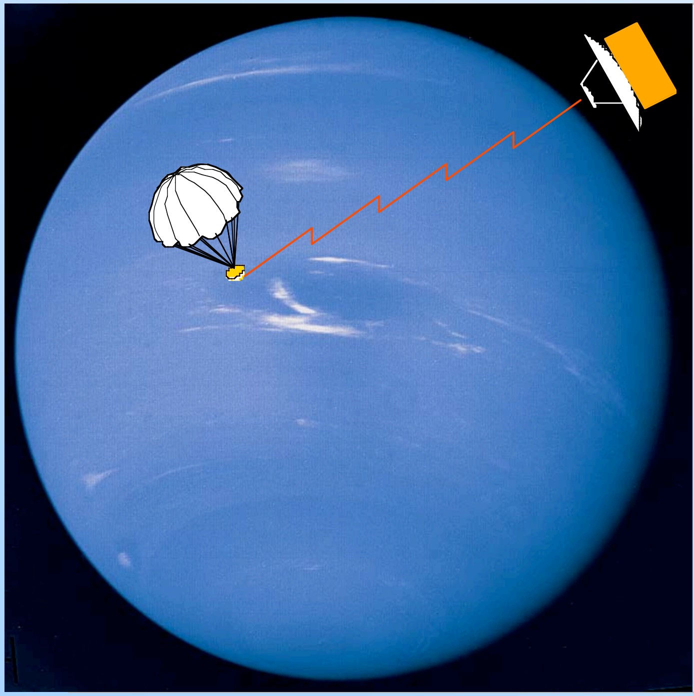
JPL Advanced MISSION STUDIES

# Entry Probe Communications at the Giant Planets

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# Organization

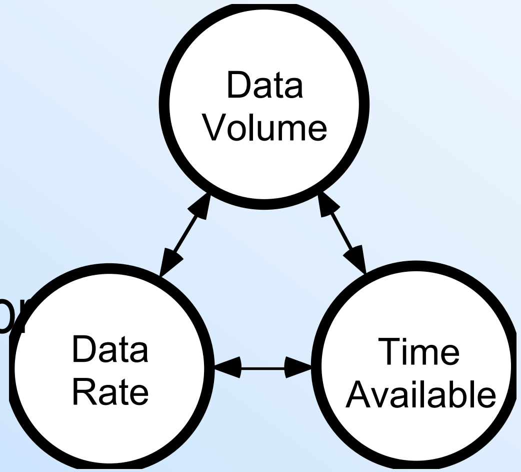
- Requirements
- Description of the Problem
- Radio Hardware Characteristics and Performance
- Radio Propagation Effects
- Geometry
- Conclusions

# Requirements

- Initial requirements come from the science community
  - What do we need to measure?
- Project requirements quickly become a trade between scientific desire and engineering capability (and budget!)
- Communications systems architecture and design must balance three critical quantities:

  *Data Volume, Data Rate, and Time*

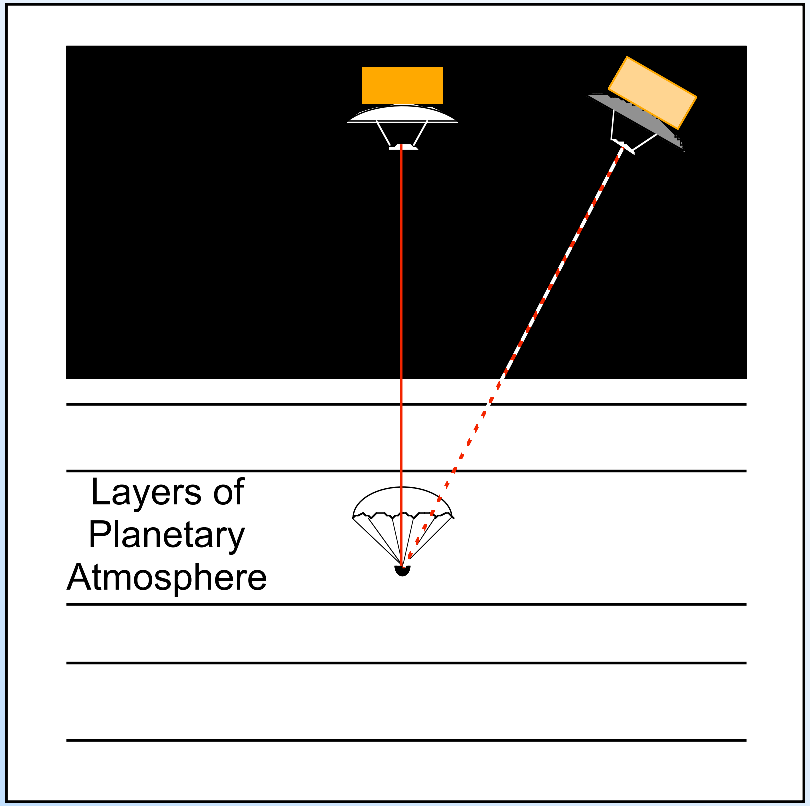
- A fourth quantity impacts the trade space for the other three:




  - Where (at what levels) should the measurements be made?

# Definition of the Problem

- A probe at some level within a planetary atmosphere ...
- ... must send a given volume of data in a given time ...
- ... through the intervening atmosphere, and possibly other non-vacuum media ...
- ... over some distance *r* ...
- ... to a receiving station of given performance.
- It is *possible* (overwhelmingly likely!) that the receiving station might not be directly overhead of the probe



# Definition of the Problem

- Approximation for a system's maximum data rate:

$$R_D \approx R_o \cdot \left(\frac{\pi}{4c}\right)^2 P_t \left(\frac{f D_t D_r}{r}\right)^2 \prod_i \xi_i$$

- or, equivalently:

$$R_D \approx R_o \cdot \frac{P_t}{16} \frac{G_t D_r}{r^2} \prod_i \xi_i$$

$P_t$: transmitter power

$G_t$: transmitting antenna *gain*

$D_r$: receiving aperture diameter

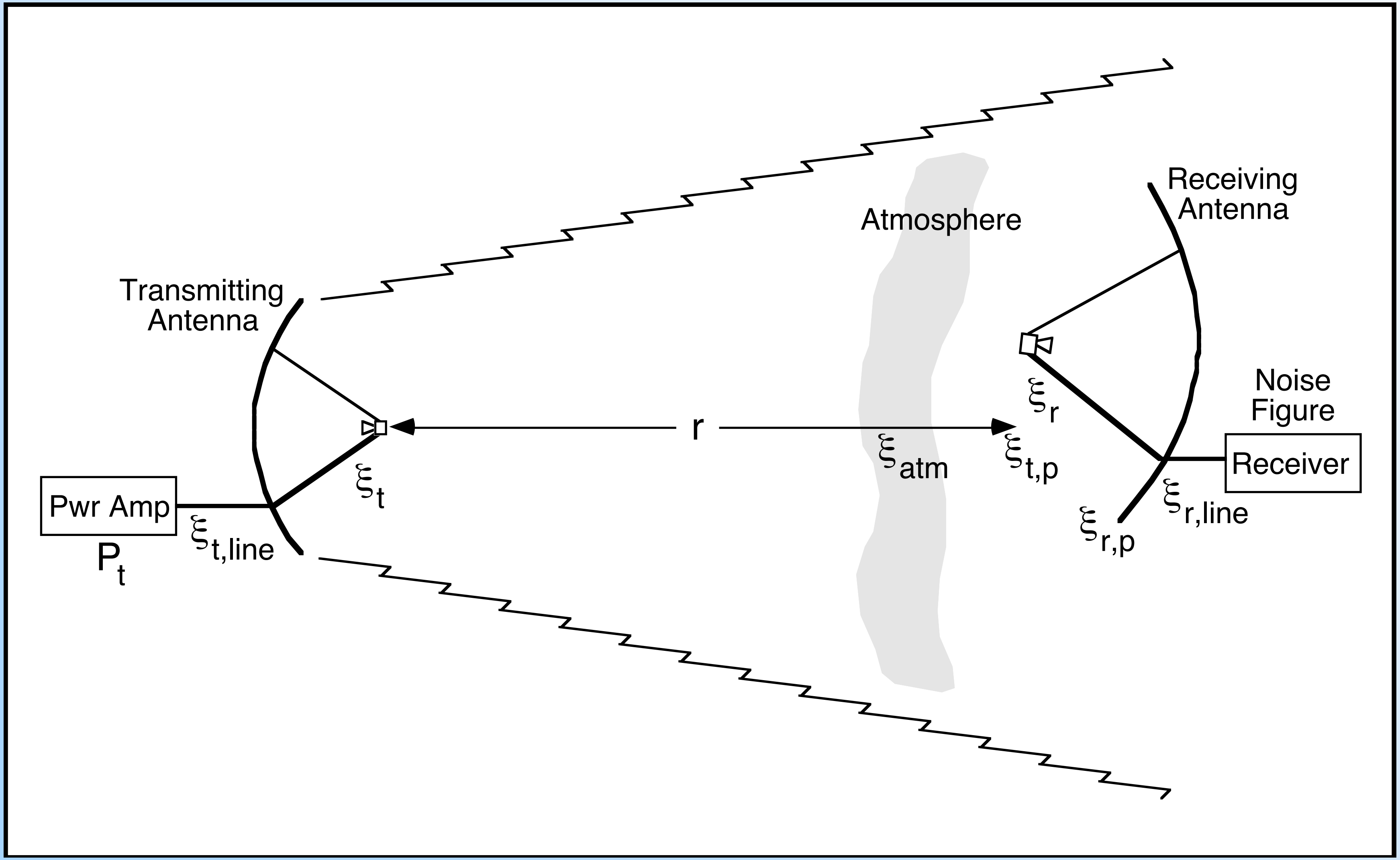
r: distance between antennas

$\xi$ : loss terms (e.g., signal absorption or scattering, antenna losses)

$R_o$: constant (approximately) of proportionality depending on the receiving system's performance, coding schemes, noise, etc.

# Definition of the Problem

## General Telemetry Systems & Loss Terms

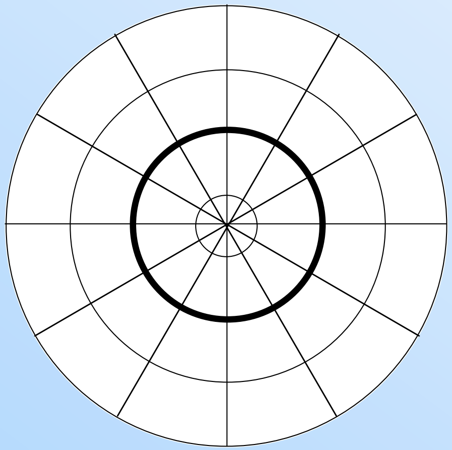


# Radio Hardware Characteristics and Performance

# Radio Hardware
# Characteristics & Performance

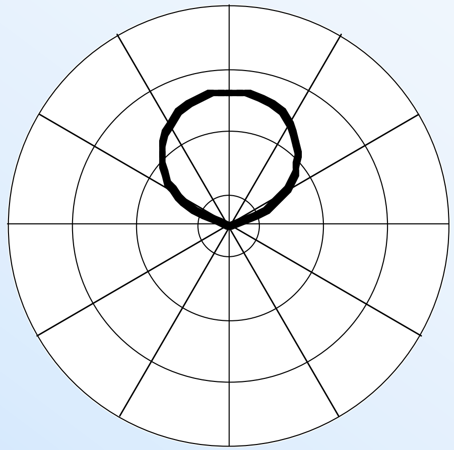
## Antenna Patterns & *Gain*

“Isotropic Radiator” (a fiction)

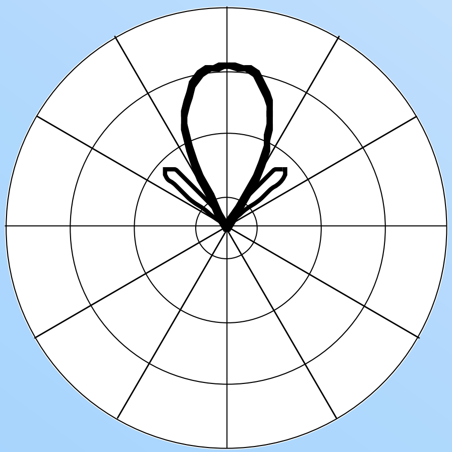


<u>Gain</u> G is the ratio of an antenna’s on-axis emitted signal intensity to that of an isotropic radiator driven by the same total power.

“Low Gain” antenna



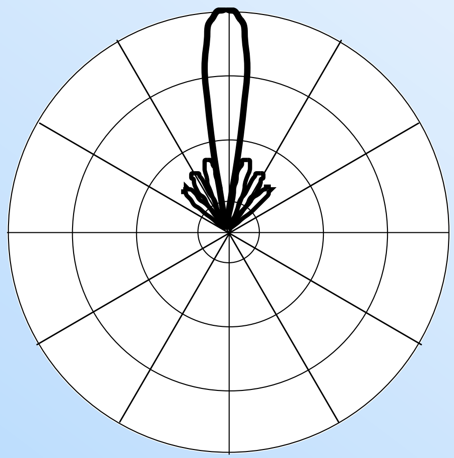
“Medium Gain” antenna



$$G = \frac{4\pi A}{\lambda^2}$$

$$= \left(\frac{\pi}{c} fD\right)^2$$

“High Gain” antenna



# Radio Hardware
# Characteristics & Performance

## Component Size, Mass, & Power

- Generally, components increase in size and mass as frequency decreases (wavelength increases; $\lambda = c/f$)
  - Typical components include antennas, connectors, directional couplers, etc.
- Usually an entry probe's largest single power consumer is the telecom system's RF power amplifier
  - Currently there are two main types of power amplifiers:
    - Traveling Wave Tube Amplifiers, or TWTAs
      - Usually heavier than an SSPA, but DC-to-RF efficiency ~50%
    - Solid State Power Amplifiers, or SSPAs
      - Usually lighter than a TWTA, but DC-to-RF efficiency 10-20%
  - Trade usually favors SSPA for low power, TWTA for high power

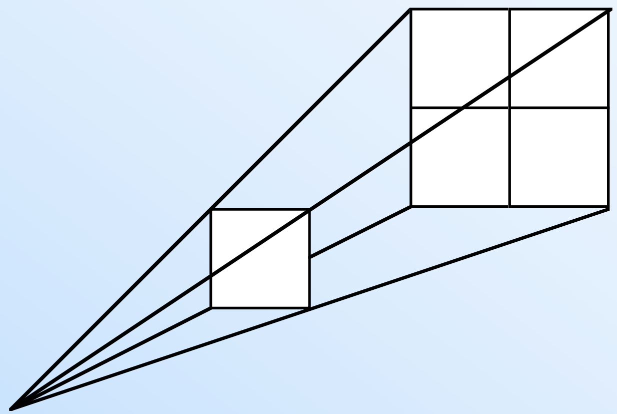
# Power Supplies

- Figures of Merit for power supplies
  - Specific energy: total energy available per mass of power system
  - Specific power: maximum usable power drain per system mass
- Most entry probe missions have descent-phase durations from one to a few hours
  - Primary batteries are excellent power sources for such missions
    - High specific energy and specific power
    - Can handle low-power missions of a few days or weeks duration
- Longer missions need more complex, and less efficient, systems
  - Solar or RPS primary source, sometimes with secondary batteries
  - Aerobots, long-duration balloons or landers

# Radio Propagation Effects

## Attenuation by Spherical Divergence

- In the "far field", radio waves propagate radially away from an antenna
  - RF power spreads over an area proportional to $r^2$
  - Intensity of the radio signal goes as $1/r^2$
    - Reason for the $r^2$ in the denominator of the $R_D$ equation
    - That's life (physics!); no way around it!



## Attenuation by Scattering

- Scattering changes the propagation direction of an EM wave
- Redirection of RF energy away from the antenna beam
- Due mostly to inhomogeneities in atmospheres
  - Gases: Temperature variations, turbulence
  - Liquids: Cloud droplets and local concentrations
  - Solids: Ice cloud particles and local concentrations
- Can also occur in planetary and interplanetary plasmas

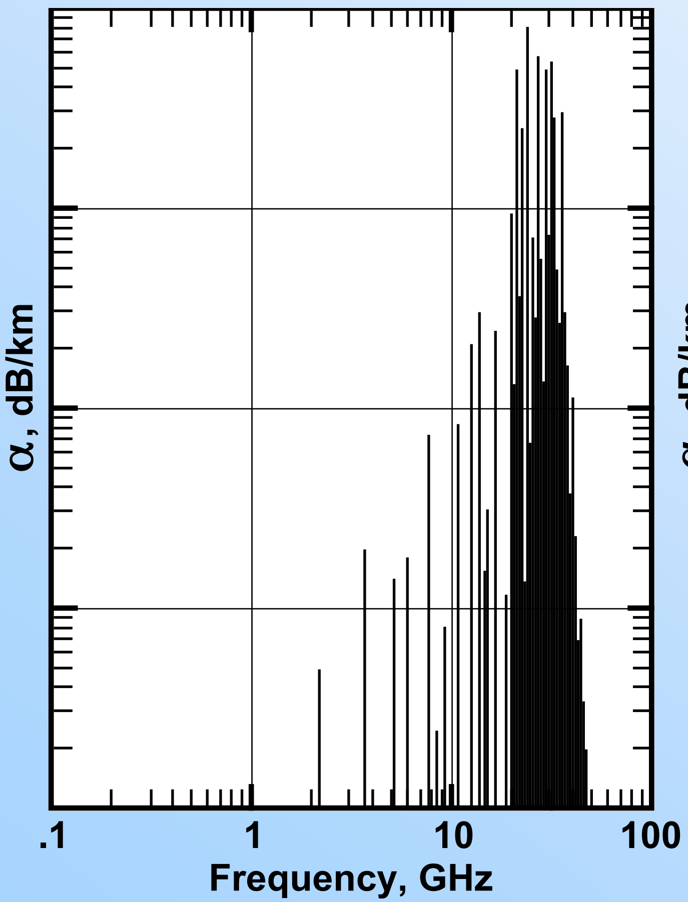
## Attenuation by Absorption

- Characterized by the “absorption coefficient” $\alpha$
  - Units of Optical Depths or dB (some *logarithmic* unit) per unit length
  - Many influences: concentration, T, P’s of other gases, radio frequency
- Many constituents of giant planet atmos’s can absorb RF energy
  - Gases: ammonia, water, hydrogen sulfide, phosphine (others?)
  - Liquids: water, water-ammonia solutions
  - Solids: water, ammonia
  - Collisional plasmas
- Absorption Spectra: absorption coefficient vs (radio) frequency
  - Liquids: usually have non-resonant “Debye” spectra
    - Absorption coefficient of a given sample is proportional to $f^2$
  - Gases: very complex behavior by some gases, especially ammonia
    - Discrete transitions within coupled rotational-vibrational states (and other transitions) generate many absorption lines
    - Pressure broadening increases line widths so they overlap, creating a continuum spectrum
    - Extreme pressure broadening produces a quasi-Debye spectrum, and can broaden powerful IR absorption lines into the RF portion of the spectrum

# Radio Propagation Effects

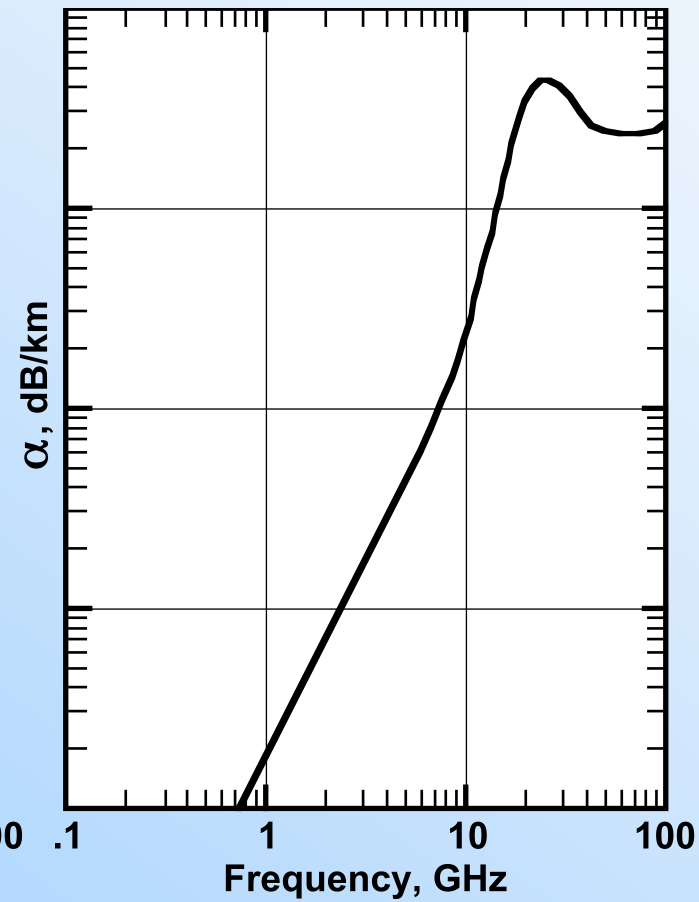
## Attenuation by Absorption in a Gas: Ammonia

Line spectrum



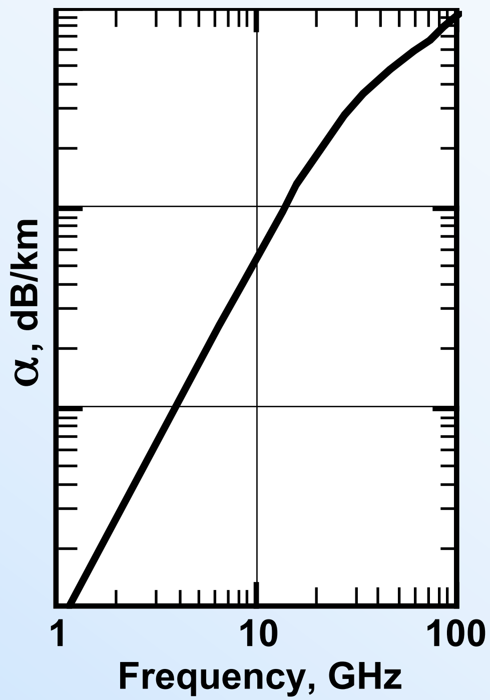

Few mb $NH_3$

Pressure broadened




+ ~1 bar $H_2$ + He

Near-Debye




+ 50-100 bars $H_2$ + He

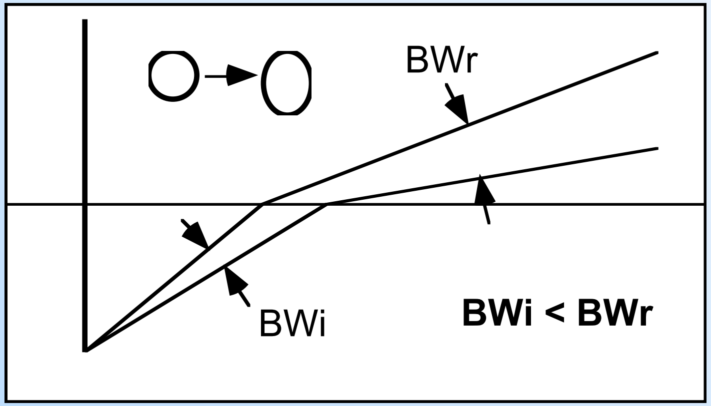
# Radio Propagation Effects: Other

## Polarization Effects

- A magnetoplasma (such as an ionosphere) can rotate the polarization plane of a linearly polarized signal
  - Degree of effect depends on plasma parameters that can vary with time
  - Receiving stations may not be able to accurately predict the polarization direction
- Circularly polarized signals are unaffected
  - Reason interplanetary communications systems use circular polarization

## Refractive Beam Spreading

- Bending of a refracted ray increases as the angle of incidence increases
  - “Bottom” of an antenna beam bends more than the “top”
  - Beam becomes elongated, spreads the energy over a larger area: attenuation



## Noise Sources

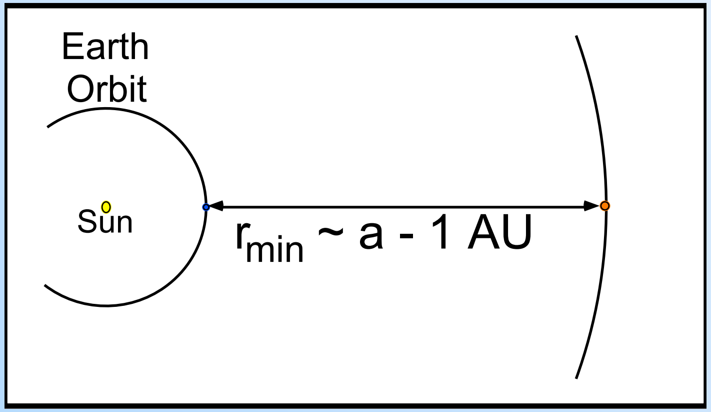
- The receiving system itself
  - Receiver internal noise (characterized by *receiver noise temperature*)
  - blackbody radiation from antenna parts
- Earth's atmosphere
  - Gases with non-zero opacity, at non-zero temperatures, radiate
    - Earth has absorbing gases, especially water
  - Scattering of noise into receiving antenna beam
- Radiation from the target planet
  - Atmospheric thermal emission
  - Synchrotron radiation, especially at Jupiter, few MHz to a few GHz
- Background noise sources: astrophysical objects, etc.
- Local (to the receiving system) interference
  - Spacecraft EMI
  - On Earth, industrial & military operations, aircraft, ground vehicles, etc

# Geometry

# Geometry

## Solar System Architecture

- The giant planets are in distant, fairly circular, nearly coplanar orbits
  - No large advantage to any particular parts of their orbits
- Opposition timing yields advantageous probe-to-Earth geometry
  - Distance is a minimum
  - Signal propagation is radial to sun



## Solar System Scales

- Fundamental unit of convenience is the Astronomical Unit or AU
  - Average distance from the Sun's center to Earth's center
  - Currently defined as 149,597,870.66 km
    - *The solar system is a <u>BIG</u> place*
- Regular planet nearest the Sun is Mercury
  - Average distance from the Sun is 0.3871 AU (0.3075 - 0.4667)
- Regular planet farthest from the Sun is Neptune
  - Average distance from the Sun is 30.0577 AU (29.8372 - 30.2782)
- Large distances cause problems for solar system exploration
  - Travel from Earth to Neptune at 965 KPH (600 MPH) takes ~515 years!
  - Telemetry data rates using "common" techniques are inadequate
    - Due to that $r^2$ in the denominator of the $R_D$ equation

# Planetary System Architecture

- Planets have non-zero *obliquity*
  - Viewing aspect from Earth (sub-Earth latitude) changes with time
  - Jupiter ~3 deg.   Saturn & Neptune ~ 30 deg.  Uranus almost 100 deg.
  - Delivery of probes to desired locations can be difficult at times
- Giant planets have moons
  - Must avoid impacts with them
  - Must ensure they do not occult the signal path
  - But ... they can be used for maneuvering within a planetary system
- Giant planets have rings
  - Some are essentially opaque at microwave frequencies
    - Saturn B ring, Uranus $\varepsilon$ ring
    - Avoid signal path occultations (may eliminate much real estate!)
- Jupiter has intense radiation belts
  - Probes to many locations must pass through them
  - Some advantageous trajectories pass through the most intense parts
    - Synchronous rotation of orbital and flyby trajectories

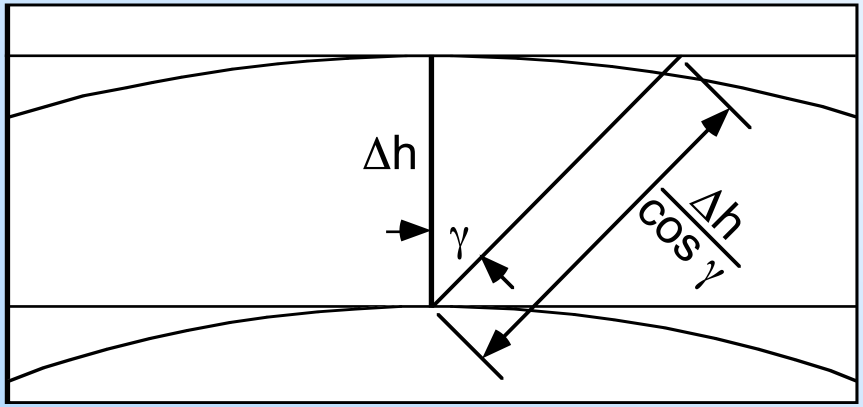
## Geometry

### Planetary Dynamics & Structure

- Giant planets rotate *quickly*
  - Probes don't "sit still" after entry; probe zenith changes quickly
- Giant planets have weather: winds, turbulence, possibly rain
  - Can scatter and/or absorb energy out of radio beam
  - Turbulence can cause large, rapid antenna pointing excursions
  - High-speed zonal winds
- Atmospheric scale heights can be large
  - Result of light gases and relatively low gravity
  - Increases absorption losses from a given pressure level
  - Ex: Saturn

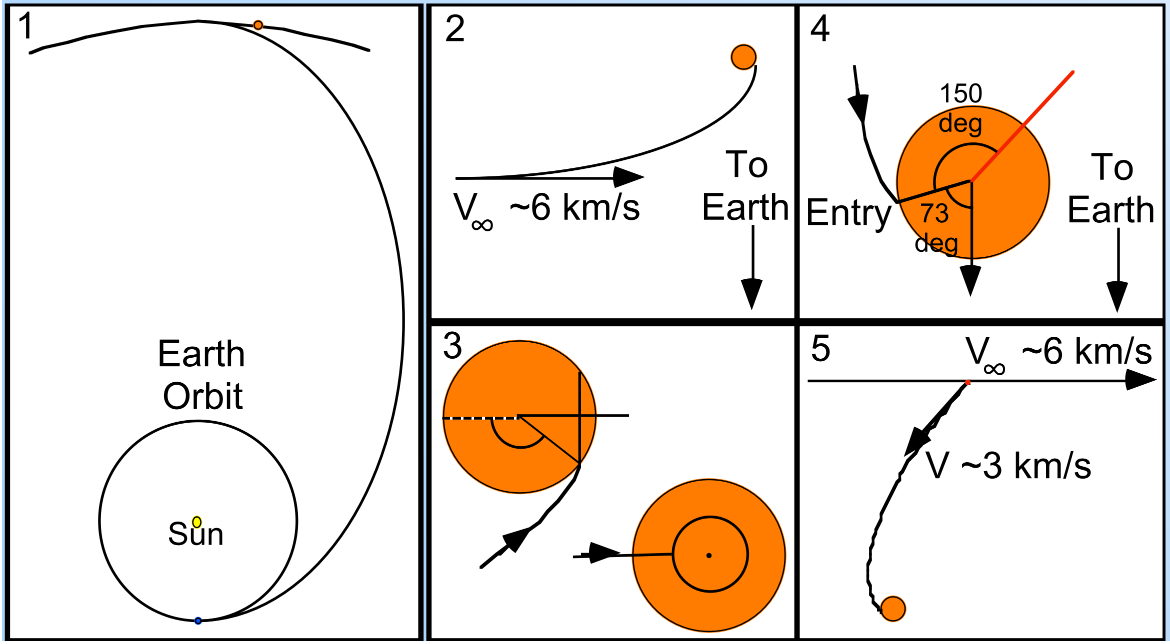
$$H = \frac{RT}{\mathcal{M}g}$$

- Giant planet sizes allow a Euclidean approximation
  - Atmospheric thickness of even several hundred km appears locally "flat"
  - Absorption *in logarithmic units* is proportional to path length!



## Orbital Dynamics Constraints

- Even the Project Manager and PI can't defy physical laws
  - Orbital mechanics is well understood at the level needed for probes
  - Some physical laws can help get around others, but it's often expensive!
- Example: Entry probe at one of Jupiter or Saturn's poles
  - Relay spacecraft cannot just "sit" above the pole -- it must be moving
  - If the RSC is not to crash into the planet, its motion moves it away from the pole
- Example: Deep entry probe at Jupiter's sub-Earth point for DTE




- Attempt to do direct-to-Earth comm generates a requirement for >7 km/s delta-V

# Conclusions

- Architecting entry probe data relay systems is a very complex, multidisciplinary task
  - Involves not just radio engineering, but also orbital mechanics, planetary and atmospheric physics, microwave spectroscopy...
- For the past 4 decades, radio system design teams have met the challenges of the design tasks
  - Analyzing performance of reasonable alternatives from their “toolkit”
  - Choosing the best architecture and system for the job
- DTE is great -- for Venus and Mars data return, and for giant planet probe Doppler measurements
- DTE underperforms for giant planet probe data return
- DTE is an old tool from the mission architect’s and radio engineer’s toolkit; they will use it *when it is appropriate*

Questions?